Phase 1: ***Development of Liquid-Vapor Core Reactors with MHD Generator for Space Power and Propulsion Applications***

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The focus of this investigation is the development of a system concept for space power generation and nuclear electric propulsion based on the Ultrahigh Temperature liquid (droplet) and Vapor core Reactors (UTVR) with Magneto Hydrodynamic (MHD) power conversion system The UTVR is a liquid-vapor core reactor concept operating with metallic uranium or uranium tetrafluoride (UF_4) vapor as the fissioning fuel and alkali metals or their fluorides as working fluid in a closed Rankine cycle with MHD energy conversion. Candidate working fluids include K, Li, Na, KF, LiF, NaF, etc. The system features core outlet temperatures of 3000 to 5000 K at pressures of about 10 to 100 atm, MHD temperatures of 2000 to 3000 K, and radiator temperatures of 1200 to 2500 K. This combination of parameters offers the potential for low total system specific mass in the range of 1 to 3 kg/KWe. The MHD output could be directly coupled to Magneto Plasma Dynamic (MPD) or other types of thruster for producing thrust at very high specific impulse ($I_{sp} =$ 1000 to 10,000 s.)

Phase 1 objectives included the development of a computational UTVR-MHD system analysis model and its application to perform performance analysis and parametric studies leading to a preliminary concept design.

Achievements of the Phase 1 project included the followings:

A system analysis code has been developed for the Ultrahigh Temperature Liquid-Vapor Reactor (UTVR) with Magneto Hydrodynamic (MHD) energy conversion system. The UTVR-MHD power system uses metallic uranium or UF_4 vapor as the fissioning fuel and an alkali metal or alkali metal fluoride as the working fluid in a closed Rankine cycle. The code calculates the system power output, specific mass, T-s diagram and thermodynamic state points, core neutronic performance, MHD generator performance, and numerous system parameters of interest.

Efforts are underway to develop a Graphic User Interface to present the code's calculational results graphically on the screen, superimposed on a schematic of the UTVR-MHD system. The developed computational model is designed to provide maximum flexibility in allowing the user to interactively change the values of many of the system parameters on the screen. This allows immediate evaluation of the effect of the change of one or more system parameters on all other system parameters. A screen display of the T-s diagram is included and will be available in the final version of the code. The code output could be also stored or directed to a printer. This expanded output includes fluids properties, individual component masses, constants used in the models, etc.

The models incorporated in the UTVR-MHD code include:

- ? Liquid (droplet) and Vapor core criticality and other neutronic parameters based on 1 and 2-dimensional S_n transport calculations, and structure and temperature reactivity effects

- ? Disk or line MHD performance based on analytical representations of a quasi-1D calculational model

- ? MHD Nozzle and diffuser based on simplified governing equations

- ? Heat exchanger and fuel/working fluid pump models based on energy and momentum balance as well as thermodynamic equations

- Fluid properties based on table look up and curve fits to JANAF-format data for the fuel and working fluids

The UTVR-MHD code is used to arrive at a baseline UTVR-MHD system design generates 200 MWe power at a specific mass of 0.4 kg/kWe for the reactor and power conversion system. The gamma ray and neutron shields are not included in the weight performance calculations. However, a conservative estimate of the weight of shielding materials indicates that a weight performance of 1 kg/KWe is achievable. The baseline 200 MWe power is generated in a disk MHD that is fed by more than 1100 MW thermal power in a 3-m3 reactor core with a 50 cm BeO reflector region. The UF_4/KF working fluid mixture enters the reflector as liquid at an inlet temperature of 1800 K at a pressure of 50 atm. The mixture boils in the reflector and enters the core at 1900 K. A separate loop of KF cools the reflector and then enters the core. A slipstream of this loop is used to cool the cavity wall before entering the core. The reactor outlet temperature is 4000 K.

The reactor outlet stream is directed through a nozzle and into the MHD channel. The MHD generator operates at an inlet Mach number of 3 and swirl of 2.5, a Hall parameter of 2.7, and a plasma conductivity of 60 mho/m. The magnetic field strength is 4 T. The exhaust of the channel is directed to a diffuser and into the main heat exchanger. In the heat exchanger, the KF component condenses first and is directed to pumps. The UF_4 is further cooled in a second heat exchanger and then routed to the pumps.

The UTVR-MHD code contains estimates for Vapor/Gas Core Reactor (V/GCR) neutron multiplication factors (k_{eff}'s). The k_{eff} results were obtained from a previously calculated one-dimensional S_n transport theory model and are for "generic" V/GCR's. Provided that reasonable correction factors are used with these data, the k_{eff} values are to within 5% accuracy. This is adequate accuracy for the purpose of this code and its overall current state of development. Refinements to the neutronics package, including improved built-in correction factors, will be provided in the future to accurately account for neutronically important features of specific UTVR concepts.

The MHD generator model used in the code is based on the governing equations of the weak interaction MHD flow of partially ionized fissioning plasma. The model considers a steady state, inviscid, tangentially symmetric, quasi-one dimensional, ideal gas flows, neglecting heat transfer effects and the effect of induced B-fields. The applied magnetic field and the thermal neutron flux profiles are treated as uniform throughout the MHD active duct region. The fission power generated as a result of high neutron flux in the MHD channel is included in the balance of power in the system.

The formulations for the nozzle and diffuser equations follow the classical derivations. The nozzle efficiency is defined as the ratio of the actual exit kinetic energy to the exit kinetic energy for an isentropic flow. The diffuser efficiency is defined as the ratio of the isentropic enthalpy change to reduce the kinetic energy to zero to the actual enthalpy change to reduce the kinetic energy to zero. The diffuser exit total pressure can be calculated with or without a normal shock at the diffuser inlet followed by compression to a very low Mach number. When the shock is calculated, the inlet variables are evaluated behind the shock. The nozzle and diffuser analysis assumes the flow is adiabatic, and therefore the energy loss is zero.

In this preliminary version of UTVR-MHD code, the effect of the heat exchangers and pumps on the system is accounted for only in the energy balance using performance efficiency. Pressure losses in these components and piping are thus not included. These effects will be included in the next version of the code that will be developed under the phase 2 and 3 of this project.

The method adopted for calculating thermodynamic properties of single species is based on the use of curve fit coefficients generated by least-square curve fit to a JANAF database. The method is the same as developed at NASA- Johnson (MSC) for project Apollo which can be considered a JANAF/NASA/industry standard. Contained in the curve fits are the heat of formation at 298 K, the sensible enthalpy difference from 298 K, the entropy at one atmosphere, and the specific heat.